Plant and Soil **148**: 115–127, 1993.

PLSO 9322

City refuse compost as a phosphorus source to overcome the P-fixation capacity of sesquioxide-rich soils

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Received 2 September 1991. Accepted in revised form 26 September 1992

Key words: compost, phosphate fertilizer, P-fixation capacity, plant P uptake, sesquioxic soils, soil P availability

Abstract

In sesquioxide-rich soils of tropical and subtropical areas and volcanic-ash soils with high levels of active Al(Fe), large amounts of phosphate fertilizers are needed to overcome their high P-fixation capacity ("quenching" strategy). A greenhouse pot experiment has been used to evaluate the effectiveness of city refuse compost (CRC) as a P-source for these variable-charge soils, compared to inorganic P. Mature CRC and K_2HPO_4 were applied at rates equivalent to 125, 250, 375, 500 and 625 kg P ha^{-1} to a ferrallitic soils from Tenerife Island (Andeptic Paleudult) with a high content in active Al + Fe (4.82%) and a high P-fixation capacity (87%). Perennial ryegrass (*Lolium perenne* L.) was grown in pots and plants were harvested at regular intervals after seedling emergence. CRC increases plant P concentration and soil labile-P proportional to the applied rate. The best results were obtained from a compost application of 30 t ha^{-1} equivalent-rate, after a residence time of at least three months. An important residual effect in the supply capacity of P in relation to the phosphate fertilizer was also observed. The relative agronomic effectiveness (RAE) in comparison to K_2HPO_4 was 66% after 6 months, considering P uptake + soil labile-P. The soil P-fixation capacity was significantly reduced from a compost application of 40 t ha^{-1} equivalent-rate. Competition in adsorption between organic ligands and phosphate, in combination with net mineralization of organic P in compost, might account for the high RAE value obtained. The main conclusion is that the city refuse compost could be a suitable P-amendment for sesquioxic soils due to its high RAE, and the residual effect on P-supply.

Introduction

City refuse compost, when well-matured, exerts a positive influence on some physical soil properties such as porosity, aggregate stability, water-holding capacity and bulk density (Hernando et al., 1989; Pagliai et al., 1981; Piccolo and Mbagwu, 1990). It also improves the humus content, the pH-buffering capacity, increases the cation-exchange capacity and releases mineral nutrients gradually (Giusquiani et al., 1988; Guidi et al., 1982; Marchesini et al., 1988). Root systems are stimulated by the improved soil physical and nutritional qualities (Pera et al., 1983). Finally, mature compost has been shown to increase plant nutrition and improve crops (Gallardo-Lara and Nogales, 1987; Iglesias Jiménez and Pérez García, 1989). City refuse compost may be an important source of P to crops (Cabrera et al., 1991; Dalal, 1977; Mehta

and Daftardar, 1984; Terman et al., 1973). However, most studies on organic residues of urban origin, such as city refuse compost and sewage sludge, have been conducted in regions with cool or temperate climates where P-deficient soils are normally uncommon (McLaughlin and Champion, 1987). The high P-fixation capacity in sesquioxide-rich soils of tropical and subtropical areas and volcanic soils with high levels of active Al(Fe) can pose agronomic problems, since the P added as a fertilizer is immediately adsorbed at the surface of metallic oxides so that plant P absorption becomes difficult (Hernando et al., 1986). One of the management strategies adopted for these variable-charge soils is to "quench" the P-fixation capacity with one or several large initial phosphate applications, up to 1000 kg P ha^{-1} in some sesquioxic soils (Younge and Plucknett, 1966). Because of the amounts of phosphate fertilizers needed, this management strategy requires a large initial financial investment, although it may be amortized over several years while the residual effect of P is effective (Sanchez and Uehara, 1980). A suitable alternative to chemical fertilizers in this "quenching" strategy may be the use of city refuse compost or sewage sludge as sources of P. Because compost and sludge are bulky materials, large single applications are much more effective in economical terms than repeated small applications (McLaughlin and Champion, 1987). Domestic composts are also valuable liming materials for acid soils due to their high Ca content and provide organic P and large quantities of organic matter (Gallardo-Lara and Nogales, 1987). The organic matter has the added benefit of improving P availability by complex formation with active Al(Fe) due to the chelating ability of hydroxyl-carboxyl ligands of the humified organic matter (Levesque and Schnitzer, 1967; Parfitt, 1979; Reddy et al., 1980). Thus, humified organic matter can significantly reduce the amount of phosphate required to maintain a solution concentration necessary for crop growth (Felleca et al., 1983; Sibanda and Young, 1986). The aim of this study was to evaluate the effectiveness of city refuse compost as a source of P in a variable-charge soil from Tenerife Island with a high P-fixation capacity. Dipotassium hydrogen orthophosphate (DHP) was used as the standard for comparison.

Materials and methods

Experimental design

The compost was obtained from the municipal solid wastes of Santa Cruz de Tenerife (Canary Islands) from a controlled piling-composting trial after 75 days of bio-oxidation and 90 days of complementary maturation. The composting system, degree of maturity and compost quality have been described previously (Iglesias Jiménez et al., 1986; Iglesias Jiménez and Pérez García, 1991; 1992). Some chemical characteristics of the final product (165 days of composting) are shown in Table 1. Prior to incorporation with the soil the sample for this experiment (8 kg) was air-dried, ground to pass a 1-mm sieve and thoroughly homogenized. The total elemental content showed in Table 1 is related to this sample (average of 5 repetitions). The pH (H_2O, 1:5) of this sample was 6.8.

The soil material used was from a ferrallitic soil (Andeptic Paleudult), a variable-charge soil from Tenerife with high active Al + Fe content and high P-fixation capacity. Halloysite was the dominant clay-mineral, and small amounts of gibbsite and allophane were also present. The

Table 1. Main characteristics of the city refuse compost

Ash (% dry matter)			38.3
Total organic carbon (g C kg^{-1} d.m.)			326
Oxidizable carbon (g C kg^{-1} d.m.)			309
Alkaline-extractable carbon (g C kg^{-1} d.m.)[a]			111
Humic acid-like carbon (g C kg^{-1} d.m.)[a]			73
Fulvic acid-like carbon (g C kg^{-1} d.m.)[a]			38
HA/FA ratio			1.9
C/N ratio in the solid phase			9.9
Corg/Norg ratio in the water-soluble phase[b]			5.4
Cation-exchange capacity[c] (cmol kg^{-1})[a]			80.1
Total elemental content:			
N (g kg^{-1})	31.0	Mn (mg kg^{-1})	321
P	12.5	Zn	1043
K	38.3	Pb	224
Ca	92.9	Cr	73
Mg	8.7	Ni	58
S	5.1	Co	15
Na	21.0	Cd	2
Fe (mg kg^{-1})	18184	Hg	2
Cu	463		

[a]On ash free material basis.
[b]Chanyasak and Kubota (1981) procedure.
[c]Harada and Inoko (1980) procedure.

chemical composition and physicochemical properties are shown in Table 2.

The pot experiment was conducted over seven months (July–December), in a controlled environment. The greenhouse was maintained at 24/16°C day/night, with natural sunlight flux. In order to study the response of perennial ryegrass (*Lolium perenne* L. cv. Vigor) to P sources, city refuse compost (CRC) and dipotassium hydrogen orthophosphate (DHP) were applied at different rates. After mixing (soil and fertilizers), 3 kg of air-dried soil were placed in 3.5 L plastic pots and treatments were arranged in a randomized complete block design (Little and Hills, 1975). Five compost treatments were set up according to the compost weight incorporated into soil: 10, 20, 30, 40 and 50 t ha^{-1} (CRC treatments). At the same time five treatments with mineral fertilizers were established (MF treatments) on the basis of the N, P, K, Ca, Mg, S, Na, Cu, Fe, Mn and Zn content of the CRC treatments. A control (C) was also established. Table 3 shows the nutrient content for the 10-CRC treatment and the chemical fertilizers used for the 10-MF treatment (analytical grade chemicals).

In each pot 1000 seeds of ryegrass (85% germination index) were planted and 400 mL deionized water was added. Germination was completed in 7 days. Plants were harvested at 30, 60, 90, 120, 150 and 180 days after seedling emergence. Pots were watered daily with deionized water to bring the soil moisture to a level corresponding to 33 KPa tension (25% moisture). The total number of pots employed was 253, 55 of which were used for plant nutrients assay (11 treatments × 5 replications) and 198 for the study of the evolution of nutrients in the soil (11 treatments × 3 replications × 6 harvesting periods).

Table 2. Some characteristics and chemical analysis of the soil used

Textural class: clay loam	
pH (H_2O, 1:2.5)	5.8
pH (KCl, 1:2.5)	4.8
EC (dS m^{-1} 25°C)	1.00
Organic matter (%)	2.85
CEC (cmol kg^{-1})[a]	21.20
NH_4-N + NO_3-N (mg N kg^{-1})[b]	53
Available-P (mg P kg^{-1})[c]	20
Available-K (mg K kg^{-1})[d]	321
P-retention capacity (%)[e]	87.0
Al_0 (g kg^{-1})[f]	25.6
Fe_0 (g kg^{-1})[f]	22.6
Si_0 (g kg^{-1})[f]	9.0
Al_p (g kg^{-1})[g]	5.7
Al_p/Al_0	0.22
Soil taxonomy: Ultisol (Andeptic Paleudult)	

[a]Fey and Le Roux (1976) procedure.
[b]Potassium chloride (2*M*) extraction (1:10 soil-solution).
[c]Olsen method (Olsen et al., 1954).
[d]Ammonium acetate (1*M*, pH 7.0) extraction.
[e]Blakemore method (Blakemore et al., 1981).
[f]Acid ammonium oxalate (pH 3) extraction.
[g]Sodium pyrophosphate (pH 9.8) extraction.

Table 3. Bioelement rate supplied by the 10-CRC treatment (10 t ha^{-1} equivalent-rate of city refuse compost) and by the equivalent 10-MF treatment (mineral fertilizer)

Element	(g pot^{-1})	Chemical product	(g pot^{-1})
N	0.464	NH_4NO_3	1.326
P	0.187	K_2HPO_4	1.051
K	0.574	K_2SO_4	0.232
Ca	1.139	$CaCl_2\,2H_2O$	1.250
		$CaCO_3$	2.620
Mg	0.131	$MgCl_2\,6H_2O$	0.880
S	0.077	$MgSO_4\,7H_2O$	0.262
Na	0.315	NaCl	0.800
	(mg pot^{-1})		(mg pot^{-1})
Fe	272	$FeCl_3\,6H_2O$	1321
Cu	6.9	$CuCl_2\,2H_2O$	18.5
Mn	4.8	$MnSO_4\,H_2O$	14.7
Zn	15.6	$ZnSO_4\,7H_2O$	68.6

Analytical determinations

For dry matter production determinations, the aerial part of ryegrass was dried at 80°C in a forced draught cabinet oven to constant weight. Dried plants were ground in a stainless steel mill to powder and stored for chemical analysis. Prior to the analytical process, the ground samples were dried again at 105°C for 2 hours. The sample mineralization was conducted by ignition (480°C) and ash was redissolved with 6 *N* HCl. From this solution phosphorus was determined according to the molybdivanadophosphoric acid procedure (Chapman and Pratt, 1961). Plant K, Ca, Mg, Fe, Zn, Mn and Cu were determined by atomic absorption spectroscopy. Plant N was determined titrimetrically following the semimicro Kjeldahl digestion method (Bremner, 1965).

Soil samples were air-dried, ground and sieved (2 mm). Labile phosphorus was extracted by the Olsen method (Olsen et al., 1954) and determined colorimetrically by the method of Murphy and Riley (1962). The choice of this bicarbonate test in this acid soil rather than an ammonium fluoride test was made in view of the results obtained by Holford (1980a, 1980b), who demonstrated that the Olsen test was correctly sensitive to phosphate buffering capacity of soil, even in moderately acid soils (from pH, $H_2O > 5.4$), and therefore gave the highest correlations with plant P uptake in comparison to Bray-Kurtz tests. These results are corroborated in a recent work by Mendoza (1989) in soils with pH from 4.2 ($CaCl_2$), who shows that the sodium bicarbonate tests (Olsen and Colwell tests) better reflect the relationship between soil P-buffering capacity and plant parameters (P uptake and relative yield) than the Bray I and Bray II tests.

Soil P-fixation capacity (ΔP) was determined by the method of Blakemore et al. (1981), by shaking 5 g of soil and 25 mL of solution containing 1000 mg P L^{-1} (pH = 4.6) for 24 h and then measuring the P remaining in solution by the molybdivanadophosphoric acid procedure. The degree of soil P-fixing capacity was expressed as percent of the added P that was fixed by the soil.

Statistical analyses

Plant and soil analysis data were subjected to Analysis of Variance (ANOVA) and Duncan's New Multiple Range Test was used to determine differences among treatments at the $p = 0.01$ probability level whenever the Analysis of Variance F value was significant (Little and Hills, 1975). The regression equations and correlation coefficients relating plant growth, nutrient uptake and soil labile phosphorus were also calculated.

Apparent bioavailability rate of phosphorus (ABR)

The measurements of the quantity of P taken up by a crop in a treatment without fertilizer (P_0) could be considered as an estimation of the P availability level in soils, during a certain period (Morel and Fardeau, 1988). Within the overall effect of a P fertilizer at a given rate of application, it is necessary to distinguish between P derived from available soil-P (P_S) and P derived from the freshly applied fertilizer (P_F) (Morel and Fardeau, 1990). Thus, the total P taken up is $P_T = P_S + P_F$.

P_F is calculated from P_T in treatments with P fertilizers minus P_0 taken up by the crop without fertilizer (control) assuming that P_S and P_0 do not differ significantly, in presence or absence of P-fertilizer ($P_S = P_0$). Then, P_F could be defined as 'apparent uptake' because the result of the control is subtracted from the total uptake (Greenwood et al., 1987). Nevertheless, taking into account results from Morel and Fardeau (1990), who used ^{32}P-labelled fertilizer, P_S can differ from P_0 in several soils: P_S-P_0 is positive in some soils poor in available P and negative for high P_0 values. In fact, the difference between P_S and P_0 is significant for a few soils. In order to compare the effect between the two fertilizers P_S and P_0 differences are assumed to be negligible.

As shown by Morel and Fardeau (1990), from P_F the following calculations can be made:

– the percent of P-fertilizer utilization: PPU% = 100 (P_F/F), where F is the quantity of P applied as fertilizer.

– P in the plant derived from fertilizer: PDFF% = 100 (P_F/P_T).

The apparent bioavailability rate (ABR) was calculated according to the expression: ABR% = 100 ($P_F + Pa_F$)/F, where Pa_F is the quantity of soil labile-P (Olsen-P) derived from the applied fertilizer. This parameter is calculated from: $Pa_F = Pa_T - Pa_S$, where Pa_T is the total quantity of soil labile-P at the end of the experimental period and Pa_S the quantity of phosphorus apparently derived from native soil P (control).

Relative agronomic effectiveness (RAE)

To compare the relative agronomic effectiveness the following expression was used:

$$\text{RAE}\% = \frac{\beta_i \text{ CRC}}{\beta_i \text{ MF}} \times 100$$

where β_i CRC (city refuse compost) and β_i MF (mineral fertilizer) represent the slopes of semilog or linear function used to describe the relationship between the quantity of P applied as

fertilizer (F) and $P_F + Pa_F$, as follows:

$$Y_i = \beta_0 + \beta_i \ln X + \varepsilon_i \quad \text{or} \quad Y_i = \beta_0 + \beta_i X + \varepsilon_i$$

where Y_i is $P_F + Pa_F$ obtained with source i, X is the rate of P applied (F), β_i is the slope of the response function, β_0 is the common intercept and ε_i is the error term of the fitted model.

The RAE expression is similar to that used by Chien and Hammon (1989) to compare the relative agronomic effectiveness of different sources of phosphorus. In this study Pa_F (soil labile-P derived from fertilizer) was also considered as well as P_F (P uptake by the plant).

Results and discussion

Soil labile-P, plant P concentration and P uptake

The increase with time of soil P-Olsen values corresponding to the treatments equivalent to 0, 10, 30 and 50 t ha^{-1} is shown in Figure 1. Generally, compost provides at least equivalent amounts of soil labile-P in relation to DHP, and the response is roughly proportional to the applied rates practically throughout the experiment. A gradual increase with time (up to the 4th month) was also observed in CRC treatments. This behaviour of Olsen-P does not occur with the MF treatments where large fluctuations were observed and the response from the 2nd month is not proportional to the applied dose. The results of the CRC treatments shows the existence of an increase with time of P availability after addition of the compost and therefore a high mineralization rate of organic-P during the experimental period, which has also been observed by other authors (Hortenstine and Rothwell, 1973; Mehta and Daftardar, 1984; Terman et al., 1973). Terman et al. (1973) reported that about 50% of total P present in compost is potentially available to crops within a short period. Dalal (1977) also indicated that, in general, a net increase in soil available-P will occur when the total P concentration of organic materials is greater than 3 g kg^{-1}, even with moderate application rates.

Plant P concentration is generally significantly higher in CRC than in MF treatments over the experimental period (Fig. 2). This response was especially noticeable from the 2nd month at high application rates (from 30 t ha^{-1}). During the

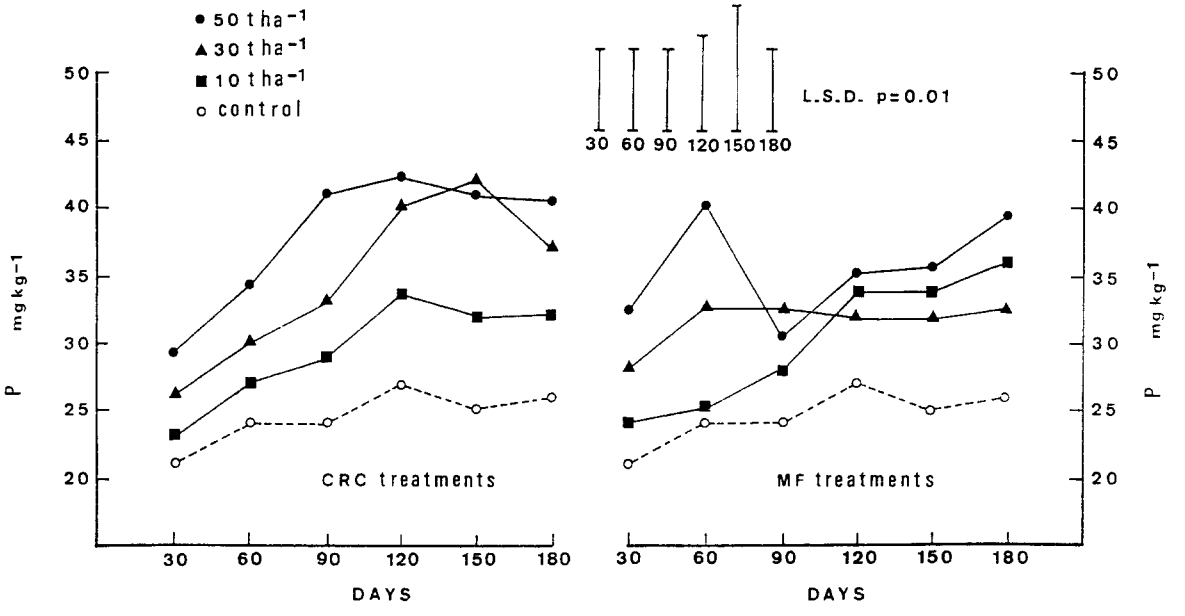

Fig. 1. Increase with time of soil labile-P (Olsen-P) for city refuse compost treatments (CRC) and mineral fertilizer treatments (MF). LSD: Least significant difference at 99% significance level.

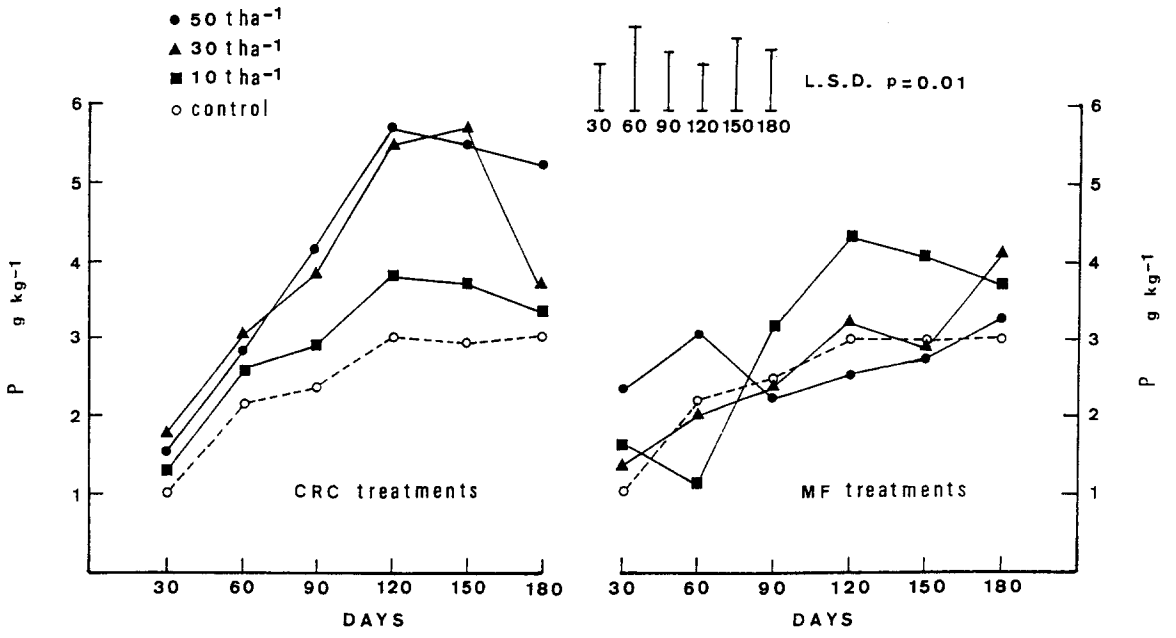

Fig. 2. Changes of P concentration with time in the aerial part of perennial ryegrass for city refuse compost (CRC treatments) and dipotassium hydrogen orthophosphate (MF treatments).

first 30 days P concentrations for both CRC and MF treatments (except 50-MF) were under the critical deficiency level for this species, 2 g kg^{-1} (Whitehead et al., 1978). This could have been due to an initial low mineralization rate (CRC treatments) and/or to a limiting effect of soil P-fixation capacity in this initial stage of the assay. From the 3rd month generally all treatments yielded values above 3 g kg^{-1}, indicating a higher mineralization of compost-P (or phosphate desorption) after a residence time of three months. From the 3rd month the differences in plant P concentration were not significantly different among the treatments 30-CRC, 40-CRC and 50-CRC. This suggests that the 30 t ha^{-1} equivalent-rate of compost is, in principle, sufficient for a suitable response in plant P concentration.

Analysis of Variance and Duncan's test for total P uptake (mg pot^{-1}) are shown in Table 4. There were only small differences between the mean values of CRC treatments, among which 10–20 CRC, 30–40 CRC and 40–50 CRC were not significant at $p = 0.01$. However, total P

Table 4. Total phosphorus uptake by perennial ryegrass grown in soil amended with city refuse compost (CRC treatments) and dipotassium hydrogen orthophosphate (DHP treatments). Duncan's test: the values with the same letter are not significantly different at 99% significance level

Materials		CRC					DHP				
Treatment rates	C	10	20	30	40	50	10	20	30	40	50
P applied mg pot^{-1}	0	187	374	561	748	935	187	374	561	748	935
P uptake mg pot^{-1}	17.5	27.9	30.9	48.4	56.5	60.0	46.8	72.8	88.8	111.4	123.4
Duncan's test ($p = 0.01$)	h	g	g	f	ef	e	f	d	c	b	a

Snedecor-F blocks: 0.14 (Snedecor-F theoretical: 3.83)
Snedecor-F treatments: 159.5 (Snedecor-f theoretical: 2.80)
Least significant difference ($p = 0.01$): 10.3 mg P pot^{-1}
Coefficient of variation: 9.705

uptake is proportional to the applied P rates. As observed in Figure 3, a highly significant correlation was found between P applied and P removed by the plant for both compost and DHP sources. The relative efficiency in P uptake (the ratio of the slopes of the regression lines as percent) was 42.5%, which is higher than those obtained for sewage sludge, generally in the range 25%–40% (Sikoda et al., 1982) but low if compared with 71% obtained by Terman et al. (1973) between urban compost and concentrated superphosphate. This result could be explained considering that the production of total biomass (dry-matter yield) was greater for MF treatments, where the nutrients supplied were in inorganic, directly available forms. Compost-N is essentially the element that determines a lower growth rate compared to the MF treatments. Nevertheless, the gradual mineralization of organic-N from compost during the experiment was enough to obtain relatively high yields after the 30 t ha^{-1} equivalent-rate (30-CRC), significantly higher than control. As can be observed in Table 4, a P uptake in the treatment 30-CRC was equivalent to that at 10-MF. The amount of inorganic-P supplied by the treatment 10-MF was already high, 187 mg P pot^{-1} equivalent to a rate of 125 kg P ha^{-1}. It should be noted that compost treatments were not supplemented with N-fertilizer (and other mineral fertilizers) in order to obtain information on the supplying capacity of compost used as the sole source of nutrients. This would obviously be the real situation in the case of the possible utilization of high rates of compost in the "quenching" strategy. Moreover, high nitrogen fertilization may induce an interaction (non-specific interaction) between N and P in higher plants: the critical level of P may increase as N content increases (Marschner, 1986). So, limiting inorganic-N supply can give information on the capacity of compost to supply P and other nutrients to the plant in conditions of N deficiency, in comparison with mineral fertilizers (relative efficiency in nutrient uptake). Our results showed that the relative efficiency in P uptake (42.5%, derived from Figure 3) was greater than that of N (14.9%), K (22.6%), Ca (23.7%), Mg (28.2%), Fe (27.1%), Zn (40.4%) and Cu (13.0%); for Mn uptake was 61.0% (unpublished results). Thus, city refuse compost, a slow-release nitrogen material, promotes a greater uptake of P in relation to the other

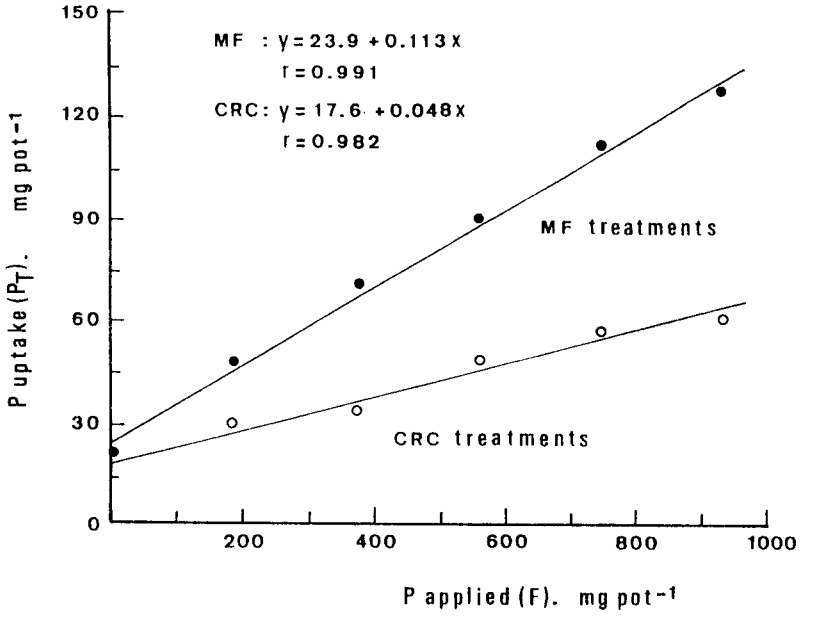

Fig. 3. Total P removed by the aerial part of ryegrass versus P applied as city refuse compost (CRC) and mineral fertilizer (MF) sources.

nutrients, and proves once more the high capacity of compost with a high maturity degree to supply P to plants.

Internal efficiency

Figure 4 shows that internal efficiency, as defined by the ratio of dry-matter yield to nutrient uptake by the plant (Khasawneh and Doll, 1978), was lower for CRC than for DHP. The ratio of the slopes of the regression lines as percent was 49%. Therefore, the plant removes about twice more P per unit of dry-matter weight from CRC than from DHP. Internal efficiency values are also shown for other nutrients in Figure 4. In the case of N, K and Mg, the fitting

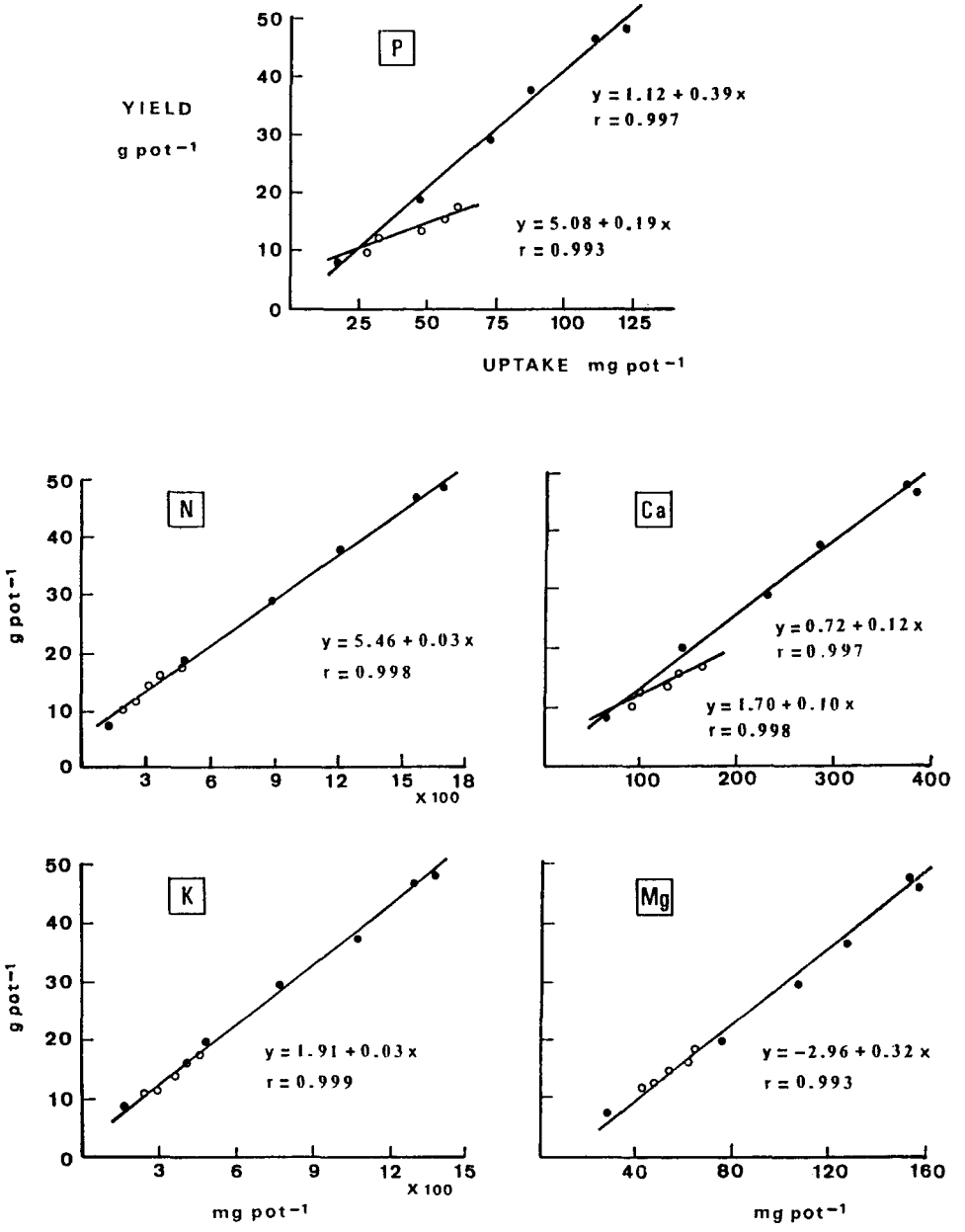

Fig. 4. Relationships between dry-matter yield and nutrient uptake (internal efficiency) for city refuse compost (○) and mineral fertilizers (●).

lines were essentially the same for both compost and mineral fertilizers, while for Ca the internal efficiency was slightly lower in compost treatments.

The internal efficiency of a fertilizer nutrient is assumed to be the same for all nutrient-sources, so that when the yield is plotted against nutrient uptake, data points from all sources and all rates fall on a single line (Khasawneh and Doll, 1978). Differences between fertilizers have been attributed to differences in nutrient uptake during early plant growth, (Chien et al., 1987), or to nutrient absorption imbalance due to a possible short supply of another plant nutrient (Mengel and Kirkby, 1987). Under our experimental conditions, N from CRC was the element determining high yields in relation to MF treatments, which may explain the differences observed in the internal efficiency for P. The observed difference between CRC and DHP also suggests a possible N-P interaction (non-specific) in *Lolium perenne*, as reported by Marschner (1986).

Apparent bioavailability rate of P and relative agronomic effectiveness

The values corresponding to the percent of P-fertilizer utilization (PPU%), phosphorus in the plant derived from fertilizer (PDFF%) and apparent bioavailability rate of phosphorus (ABR%), are given in Table 5 for the five DHP and compost treatments.

The PPU% for CRC treatments ranged from 3.6% to 5.6% of P applied with a mean value of 4.9%, far removed from the 26% observed by Hortenstine and Rothwell (1973) in a year but in a non-sesquioxic soil. The PPU% for DHP in this soil showed a mean value of 13.4% (range: 11.3%–15.7%).

The PDFF% increased gradually with the increasing application rate, both for CRC and DHP. Similarly, the CRC/DHP ratio increases proportionally to the applied dose, presenting quite high values (CRC/DHP ratio >80%) from 40 t ha^{-1}. For compost, PDFF% is only 37% and 43% for the 10-CRC and 20-CRC treatments, respectively. That is, around 60% of P in the plant apparently proceeds from the original soil reserves. Starting from the 30 t ha^{-1} equivalent-rate, the PDFF% of compost became stabilized between 64% and 71%. Thus, even for high compost rates, between 30 and 35% approximately is derived from native soil-P. Indeed, a high P retention capacity does not necessarily imply a low availability of P reserves in some sesquioxic soils, as Hernández Moreno et al. (1990) have suggested. It would thus be necessary to carry out more in-depth studies about the mechanisms of adsorption and desorption of phosphate by the Al(Fe) active compounds of these variable-charge soils to deduce the lability

Table 5. Percent of P-fertilizer utilization (PPU%), phosphorus in the plant derived from fertilizer (PDFF%) and apparent bioavailability rate of phosphorus (ABR%) of the treatments with city refuse compost (CRC) and dipotassium hydrogen orthophosphate (DHP)

	Rate (t ha^{-1} compost)				
	10	20	30	40	50
	P applied mg P pot^{-1}				
	187	374	561	748	935
PPU% CRC	5.6	3.6	5.5	5.2	4.5
PPU% DHP	15.7	14.8	12.7	12.6	11.3
CRC/DHP ratio (%)	35.5	24.2	43.3	41.5	40.0
PDFF% CRC	37.3	43.4	63.8	69.0	70.8
PDFF% DHP	62.6	76.0	80.3	84.3	85.8
CRC/DHP ratio (%)	59.6	57.1	79.4	81.9	82.5
ABR% CRC	15.0	10.7	11.4	10.4	9.1
ABR% DHP	31.6	21.1	16.4	17.4	15.8
CRC/DHP ratio (%)	47.5	50.7	69.5	59.8	57.6

degree of phosphate, essentially amorphous oxyhydroxides, allophane and organomineral complexes with reactive Al(Fe)-OH groups.

The ABR% for compost showed a mean value of 11.3% (range: 9.1%–15.2%) and 20.5% for DHP (range: 15.8%–31.6%). These values represent the fraction of apparently bioavailable P supplied (P uptake + soil labile-P, as percent of total P applied: $100(P_F + Pa_F)/F$). Therefore, between 68% and 84% of the applied P by DHP (mean of 79%) has been immobilized, supposedly by soil Al(Fe) active compounds. As already seen, there is a positive response in plant P concentration and soil available-P, in spite of the high P retention capacity of the soil.

Figure 5 shows the change in "apparent bioavailable phosphorus" ($P_F + Pa_F$) from CRC and DHP in relation to time (P-supply) corresponding to the treatments equivalent to 10, 30 and 50 t ha^{-1}. Rates of P-supply versus time from DHP declined rapidly until 90 days, especially for the high dose (50-MF). In contrast, rates of P-supply from CRC remained practically stable with a slight decrease between 30 and 60 days. Therefore, the relative efficiency in P-supply (CRC/DHP ratio) increased with time. This result suggests that CRC may be regarded as a slow-release P fertilizer in the sesquioxic soil studied, in relation to DHP. This is a characteristic of particular merit when considering using compost as a P-amendment in soils having high P-fixation capacities, as demonstrated by McLaughlin and Champion (1987) with sewage sludge, since the utilization of annual maintenance application rates of phosphate would probably be reduced.

The relationships between P applied (F) and the apparent bioavailable phosphorus derived from fertilizer ($P_F + Pa_F$) at the end of the six months of the experiment are shown in Figure 6. Relative agronomic effectiveness (RAE) was 66.4%.

Effect of city refuse compost on soil P-fixation capacity

Soil P retention capacity decreased proportionally to the compost application rate, from 87.8% (control) to 81.8% (50 t ha^{-1} rate). This reduction was significant in relation to the control from the 40 t ha^{-1} rate, and was negatively correlated to the increasing amounts of soil organic carbon ($\Delta P = 99.4 - 6.35\,TOC$, $r = -0.826$, $p = 0.042$). This result could probably be explained by the blocking effect of "humic"-type compounds supplied by compost on active

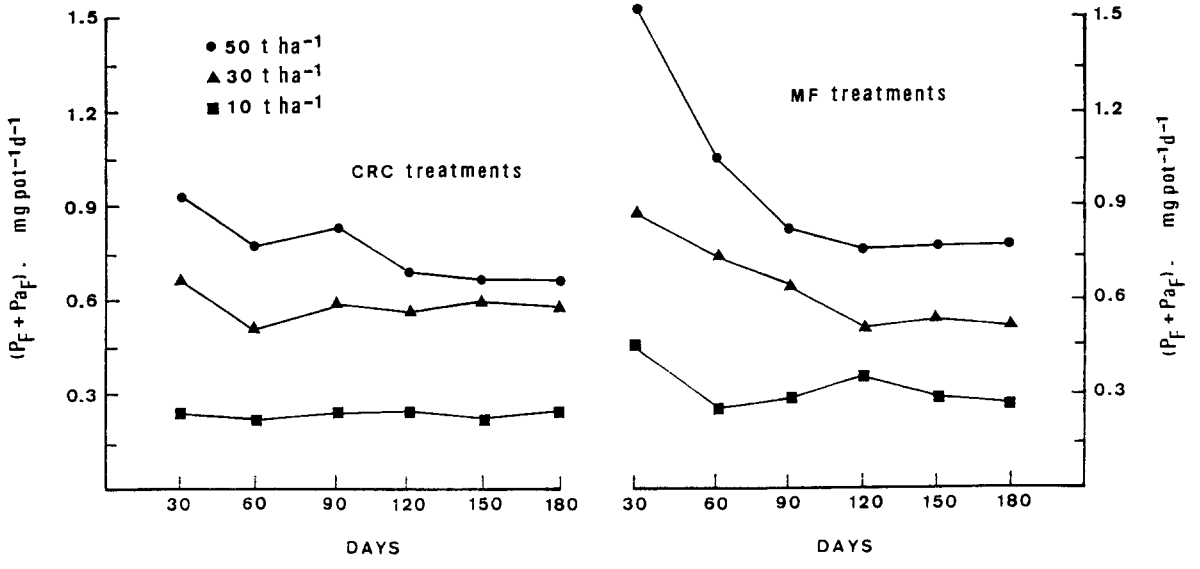

Fig. 5. Variations of the apparent bioavailable phosphorus ($P_F + Pa_F$) from city refuse compost (CRC) and P mineral fertilizer (MF) in relation to time. P_F: P removed by the plant, derived from the applied fertilizer. Pa_F: soil labile-P derived from the applied fertilizer.

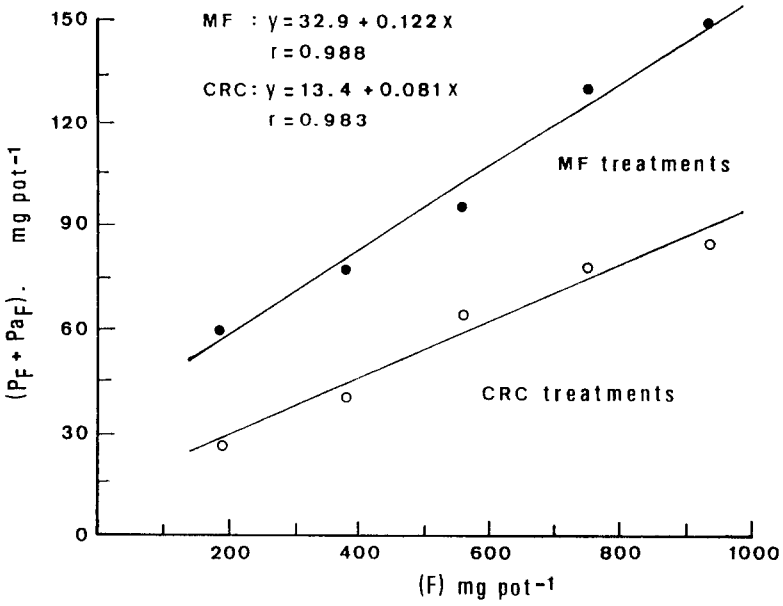

Fig. 6. Relationships between P applied by city refuse compost (CRC) or P mineral fertilizer (MF) and the apparent bioavailable phosphorus ($P_F + Pa_F$). P_F: total P taken up by the aerial part of ryegrass during all the experimental period, derived from the applied fertilizer. Pa_F: soil labile-P at the end of the experiment, derived from the applied fertilizer.

Al(Fe) surface sites. Significant reduction in phosphate adsorption by metallic oxides, due to the competitive effect between phosphate in soil solution and organic ligands, or the ability of organic materials to "block" P adsorption sites in sesquioxic soils have been reported by Fox and Kamprath (1971), Levesque and Schnitzer (1967), Moshi et al. (1974), Parfitt (1979), Reddy et al. (1980), Sibanda and Young (1986) among others.

This competition in adsorption between organic ligands and phosphate, in combination with net mineralization of organic P in compost, might account for the high RAE value obtained. Thus, city refuse compost with a high maturity degree could be a suitable P-amendment for sesquioxic soils to supply the large initial inputs of P needed to overcome the P-fixation capacity in order to bring unproductive soils up to economic levels of production, and to maintain an important level of residual phosphorus.

Acknowledgements

The authors greatly appreciate the helpful suggestions of Dr M T Felipó Oriol, Universidad de Barcelona, Laboratorio de Edafología. Special thanks to the C.S.I.C. and Caja-Canarias for financial support to perform this work. The authors are also grateful to Pauline Agnew for revising the English translation of the manuscript.

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Section editor: H. Lambers